STREAM HABITAT RESTORATION GUIDELINES
CHAPTER 2

STREAM PROCESSES AND HABITAT

Process (n):

1. **:** a natural phenomenon marked by gradual changes that lead toward a particular result <the process of growth>
2. **:** a natural continuing activity or function <such life processes as breathing> (from Merriam-Webster On-line Dictionary)

Included in the history of human-caused disturbance of stream channels is a record of intervention undertaken to improve aquatic habitat. Among these, in the cases where stream processes were not understood, is a legacy of expensive failure. Most attempts to directly build habitat elements into streams have failed due to a lack of understanding of the dynamic processes that build, maintain, and destroy habitat[1]. Too often, these attempts have further **degraded** the habitat they sought to restore. Sustainable habitat restoration requires that the full array of stream processes be maintained within, or restored to, a range of variability similar to that occurring naturally. These stream processes, in turn, require that riparian and watershed processes are similarly maintained or restored. There is growing recognition that true recovery of our stream ecosystems requires understanding, and working effectively with, the physical and biological processes that form and maintain habitat [2 3 4 5 6 7]. This chapter provides a simplified overview of the watershed and stream/floodplain processes that create aquatic and riparian habitat, and briefly describes characteristics of stream habitat

2.1 Watershed Processes

In physical terms, a watershed is an area from which water drains to a common point. This trait results in a set of physical and biological interactions and processes that causes the watershed to function as an ecological unit. Watersheds can be considered at a range of nested scales, beginning with the area contributing to a small first-order stream (i.e., a stream with no tributaries - refer to the *Hydrology* appendix for a discussion of stream order) and culminating with the world's great river basins (such as the Amazon, Nile, Congo, Mississippi, Columbia, etc). Ultimately, stream processes that create habitat integrate the physical and biological processes occurring across the contributing watershed.

2.1.1 Watershed Components

Across landscapes, two controlling factors - climate and geology - create three basic ecosystem components: soil, vegetation, and water (*Note: the effects of animals on soil and vegetation will be ignored for the sake of simplicity*). These components are overlaid on, and influenced by, **topography** that is also shaped by climate and geology. Within watersheds, the interactions of these components result in yields of streamflow and sediment with patterns of timing, quantity, and quality characteristic of each watershed. These yields of water and sediment, in turn interacting with riparian vegetation (and, in steep, forested watersheds, large wood delivered from upland sources), form the stream channel and associated aquatic habitat.

Soil

The soil mantle is a natural storage reservoir for water delivered to the watershed, absorbing rain or snowmelt and gradually transmitting it down slope. Thus, water stored in the soil is a primary source of streamflow between storms or periods of snowmelt. The storage capacity of soil depends on its depth and texture, (i.e., the total pore space available). The rate at which soil water is delivered to the stream system depends on slope, and soil texture and structure. Well-developed soils have many sizes of pores with varying degrees of connectedness. Large pores allow rapid **infiltration** and drainage of water to and from the soil mass; small pores absorb water more gradually and retain it longer, making water available during dry periods for use by plants, or for slow seepage into the stream system.

The development of soil depends upon geology, topography, time, climate, disturbance factors, and biological agents (e.g., vegetation and soil organisms). The protective vegetative cover above ground and stabilizing strength of roots below ground are critical to soil development and stability, particularly on steep slopes.

Vegetation

Vegetation performs a variety of functions on the watershed scale. It provides strength and roughness across the surface of the watershed, thereby slowing the movement of water and increasing resistance to **erosion** while promoting the development of deep soils. The vegetative canopy intercepts **precipitation**, allowing a portion to evaporate before reaching the ground, but subsequently inhibiting evaporation from the ground surface. Water use by vegetation (i.e., **evapotranspiration**) removes water from the soil. Vegetative litter slows **overland flow** and protects the soil surface from raindrop impacts, preventing splash erosion and the sealing of surface pores. Root channels increase infiltration capacity. The presence of decayed vegetation and other organic matter characterizes the topsoil, and greatly influence its properties and structure.

Water use by vegetation reduces total runoff from the associated land areas. However, the combined influences of vegetation and soil also greatly attenuates the movement of water through the watershed, dampening **peak flows**, sustaining streamflow during dry periods, and maintaining high water quality.

Water

Quantity, quality and timing of water discharged from a watershed are integrated results of watershed processes. Distributed across the landscape in the form of rain or snow, water is transported through the watershed, leaving by way of transpiration, evaporation, streamflow, and **groundwater** flow. Climate, topography, soil, and vegetation control the processing of water through the watershed. Because the combination of these factors is unique to each watershed, the characteristic timing and magnitude of flows through the stream system constitute the ‘signature’ of the watershed. For example, arid watersheds, in addition to sparse vegetation, typically have thin, poorly developed soils with low infiltration rates and little water-holding capacity. Where arid conditions are combined with steep terrain, runoff tends to occur rapidly following precipitation events, resulting in a 'flashy' **hydrograph** that peaks and declines swiftly. Conversely, where climate supports dense vegetation, an undeveloped watershed with gentle relief will tend to gradually yield high flows that gently peak and taper off into strongly sustained base flows. Characteristic elements of the hydrologic "signature" of watersheds include: 1) high flows - reflecting snowmelt, prolonged winter rainfall, rain-on-snow events, or intense summer rainstorms, 2) rates of **recession** from peak to low flows, and 3) low flows – reflecting groundwater discharge, or water released from natural storage features such as wetlands and lakes.

Snow packs provide significant water storage in many Pacific Northwest watersheds. At one extreme, high-elevation glaciers are long-term features that produce the greatest streamflow during the hottest part of the year. At the other extreme, low-elevation, transient snow packs may accumulate and melt several times during a single season, creating brief, mid-winter high flow events. Intermediate between the two are seasonal snow packs that accumulate during late fall, winter, and early spring and melt during late spring and summer. These produce a snowmelt runoff pattern that gradually increases until late spring or early summer and then gradually declines.

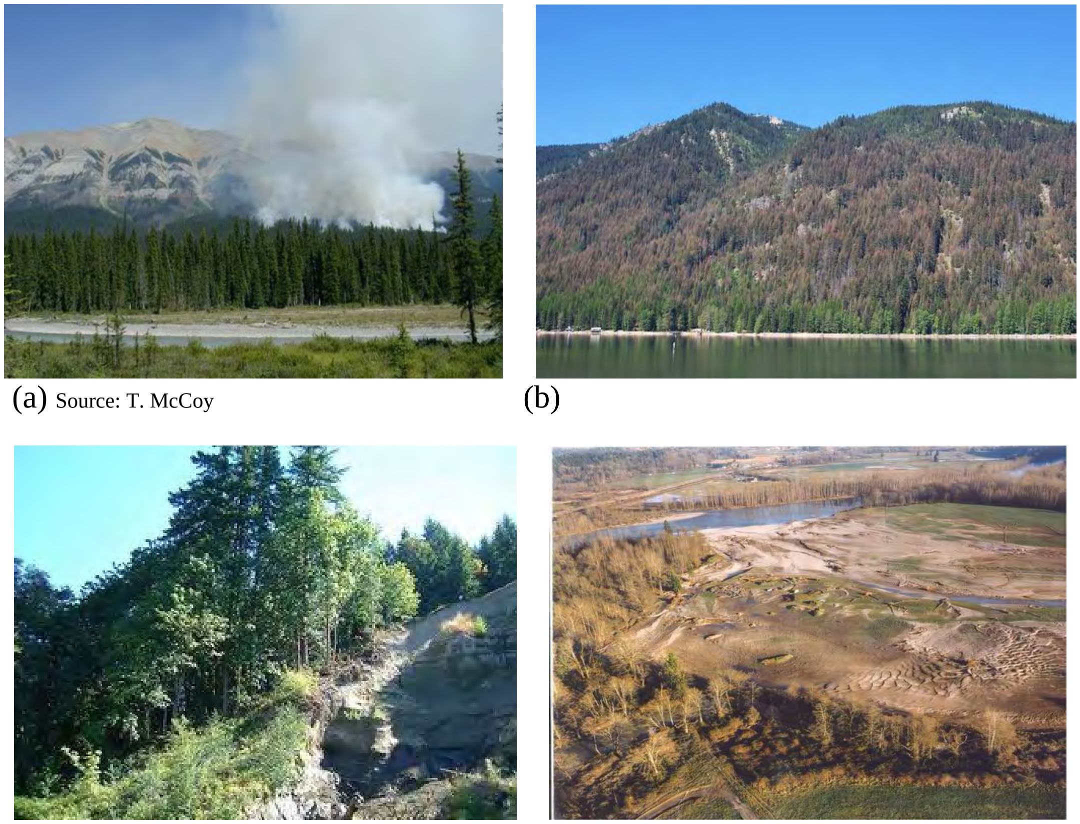
In watersheds where rainfall is the dominant form of precipitation, runoff occurs in response to storm events and the ability of the watershed to store precipitation. To a large degree, this ability is dictated by soil moisture conditions prior to the onset of the storm. Obviously, frozen and saturated soils have virtually no storage capability, and rain falling on them will be quickly delivered to the stream system. Conversely, rainfall delivered at the end of a long, dry period may do no more than replenish soil moisture, causing little response in streamflow.

2.1.2 Influence of Disturbance on Watershed Processes

The concept of disturbance is so central to understanding ecosystem functioning that it is worth providing a definition for the term at this point:

> *"Any relatively discrete event in time that disrupts ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment"* (Society of American Foresters, 1996).

Periodic large- and small-scale disturbance is critical to ecosystem functioning, resetting the '**successional** clock' and preventing the vegetative community from maintaining a homogeneous climax state. Under natural circumstances, disturbances (e.g., fire, disease, landslides, and flooding – see **Figure 2.1**) within an ecosystem occur with characteristic frequencies, intensities, and extents. Thus, every ecosystem evolves with a particular **disturbance regime**. Within a given ecosystem, the variability of size, intensity, and frequency of different disturbance events creates a mosaic of vegetation at various successional stages.



(a) Source: T. McCoy (b)

(c) (d)

Figure 2.1. a) Fire. b) Insect outbreak leading to tree mortality. c) Deep-seated landslide. d) Aftermath of flooding.

Over a landscape scale, the disturbance-driven mosaic tends to remain in dynamic equilibrium during a given climatic period. It is the diversity inherent in this mosaic that provides diverse habitat[8 9 10]. For example, many species of plants and animals are dependent on early- to mid-successional stages (biological diversity commonly peaks at the mid-successional stage). The availability of this habitat type limits the populations of numerous species.

Vegetation, in turn, interacts with the disturbance regime. For instance, among plant communities, the accumulation, distribution, and type of fuel vary greatly. These are major factors in fire frequency and intensity, which in turn strongly affects the species composition and structure of the plant community. For example, the grasses in ponderosa pine/grassland systems quickly generate continuous, low, fine fuels that support frequent, low-intensity ground fires. This type of disturbance, maintained by the fire-adapted plant community, in turn maintains the plant community by thinning young, fire-sensitive ponderosas, rejuvenating the grasses, and preventing fire-intolerant plant species from establishing.

At the other extreme, the interval between natural fires in the forests of the maritime Northwest is likely to be hundreds of years, allowing the eventual dominance of late-succession, fire-intolerant species, such as western hemlock. In these ecosystems, however, fires occur with stand-replacing intensity that allows the establishment of early-succession plant species that require full sunlight and bare mineral soil, such as Douglas fir. Because disturbance plays a dominant role in shaping the vegetative community, it is also critical to watershed functioning.

2.1.3 Erosion and Sediment Yield

Erosion is a natural process, made inevitable by gravity, wind, the weathering of rocks (i.e., soil formation), and the energy of flowing water. Erosion processes and rates are controlled by climate, topography, soils, and vegetation. Forested landscapes generally undergo little or no overland flow or surface erosion, with the organic litter on the forest floor sustaining infiltration rates greater than rates of rainfall or snow melt. In contrast, in arid or semi-arid landscapes with partially exposed soil, surface erosion may be the dominant erosional process.

Erosion rates tend to be episodic and linked to disturbance and weather. Substantial **surface erosion** occurs following the removal of vegetation with extreme rates occurring after severe fire consumes the protective organic layer and exposes bare mineral soil. **Mass-wasting** (i.e., landslides, debris flows, etc.) is the result of the gradual accumulation of soil in unstable locations, combined with a triggering mechanism, such as soil saturation, that activates the event. **Streambank erosion**, the process by which water loosens and wears away soil and rock from the edge of a stream, generally occurs during high flow events. **Figure 2.2** illustrates the different types of erosion. All three types of erosion peak during storms or periods of rapid snow melt.

(a)

(b) Source: Paul Bakke

(c)

Figure 2.2. a) Surface erosion from a road. b) Mass-wasting. c) Bank erosion.

Sediment, alternating between moving in brief pulses and being stored in channels or floodplains, is a major watershed product naturally transported and discharged by stream systems. In the same way that a given watershed produces a characteristic streamflow regime, it also has a characteristic sediment budget over time. The budget, consisting of both sediment quantity and quality (i.e., the distribution of particle sizes transported) is largely a reflection of the climate, geology, topography, vegetation, and disturbance regime across the watershed.

2.1.4 Land Use Effects on Watershed Processes

The effects of widespread land use tend to accumulate within watersheds, both over time and in the downstream direction. Any land use altering one of the three basic watershed components - soil, vegetation, or water - will affect watershed functioning. Land use (e.g., logging, grazing, farming and urbanization) generally alters vegetation, often intercepting and diverting the movement of water. Land use may also directly affect the soil through compaction. Road building, in addition to removing vegetation, exposing soils, and creating impermeable surfaces, can drastically alter the routing of water through watersheds. Numerous attempts to increase runoff by removing vegetation have had serious unintended consequences such as greatly increased erosion, earlier, flashier runoff, and correspondingly decreased base flows (i.e., more water when it is not desired and less water when it is in short supply).

Reduced vegetation, soil compaction, soil exposure, and increased velocity of water movement result in increased erosion. Erosional processes, once altered, often accelerate over time: overland flow across exposed soils creates **rills** that rapidly develop into **gullies**; sheet flow becomes channelized (expanding the drainage network), and more erosive. Expanded **drainage networks** reduce soil water storage by capturing water at the soil surface (reducing infiltration), and intercepting soil water (speeding the drainage of the soil mantle). Soil erosion in excess of soil formation, and compaction that lowers the ability of the soil to absorb water combine to reduce the water storage capacity of the soil mantle. Severe erosion alters both soil depth and quality, causing irreversible changes to the vegetation.

Quantity, quality, and timing of streamflow are the result of overall watershed processes. In the absence of climate change, changes to these processes, and by association, to aquatic habitat, reflect the cumulative effects of land use. A general effect of many land uses is to reduce the resistance offered to water as it moves through the watershed, speeding runoff, increasing peak flows and decreasing low flows. Examples of this include intensive timber harvest, road building, grazing, and urbanization. An exception to this phenomenon occurs when a significant portion of a watershed undergoes conversion from one plant community to another that is more water-consumptive. An example of this is the conversion, through fire suppression, from an open fire-tolerant forest stand to a densely stocked, closed canopy, fire-intolerant forest stand. In this case, the entire range of flows produced by that land area might decline. A case in point can be found in eastern Oregon, where widespread conversion from sagebrush-steppe vegetation to juniper woodlands has resulted in formerly perennial streams converting to **intermittent** (i.e., seasonal) flow patterns.

Ecologically, land use represents a change to the disturbance regime of an ecosystem. Fire may become much less frequent due to grazing, logging, and fire suppression. The magnitude and frequency of flooding may change. The effects of droughts may become more severe due to soil loss, soil compaction, and faster delivery of water to the stream system. Landsliding may increase due to destabilization of slopes following logging and road building (See **Figure 2.3**). Agriculture and urbanization represent major disruptions of native plant communities and ecosystems; additionally, irrigation and other water uses are inevitably associated with alterations to streamflow and groundwater.

Figure 2.3. Erosion initiated by poor road drainage.
Source: Paul Bakke

Aquatic and terrestrial ecosystems evolve within a natural range of disturbance frequency and intensity. Each system has some resistance to change and some resilience in recovering from disturbance. If the effects of human activities substantially differ from those of the natural disturbance regime, the ecosystem will be substantially altered. Ecosystem degradation is the result of imposing disturbances that are beyond the system's ability to resist or recover from.

2.2 Stream/Floodplain Processes and Attributes

2.2.1 Stream Types

A corollary to the concept that stream systems are an integration of upstream watershed processes is that channels and floodplains reflect the landscape setting. Between the extremes of high gradient mountain streams coursing down boulder-strewn beds and meandering low gradient rivers is an array of typical stream morphologies. These have been described in a variety of typing systems (e.g., Leopold and Wolman 1957[11], Schumm (1977)[12], Mollard (1973)[13], Church (1992)[14], Kellerhars et al. (1976)[15], Rosgen (1994)[16], and Montgomery and Buffington (1998)[17]).

For the purposes of this discussion there is one overridingly important stream type concept. Alluvial (or unconstrained) stream channels are formed in sediments previously transported and stored by the stream. Alluvial streams are also characterized by the presence of floodplains. Non-alluvial (or constrained) stream channels are controlled by materials they cannot mobilize, such as bedrock or large boulders (see **Figure 2.4**). Constrained stream channels tend to be very stable and resistant to change (for better or worse). As such, constrained streams are rarely the targets of stream restoration efforts.

(a) Source: Paul Bakke **(b)** Source: E. Salminen

Figure 2.4.
a) An alluvial or unconstrained stream. b) A bedrock-controlled or constrained stream.

Broadly speaking, the morphology of alluvial streams is a reflection of interactions among available energy, water, sediment, and structural elements (such as large wood and beaver dams). These are mediated by the stabilizing influence of vegetation, and, sometimes, the extent of the available floodplain. Channel geometry (i.e., the varying width, depth, slope, and **planform**) adjusts toward an equilibrium whereby the energy of the streamflow during **bedload**-moving high flows is just sufficient to maintain a balance between sediment delivery to the reach and sediment export from the reach[18]. Alluvial channel geometry alters in response to changes in independent factors such as streamflow, the supply of large wood or sediment, or to disturbance. The need for restoration of unconstrained streams is usually created by channel adjustment (i.e., **degradation** caused by excessive erosion or **deposition**) in response to changes imposed by human activities. Likewise, it is usually unconstrained streams that 'misbehave' through flooding or channel adjustments, motivating human manipulations. The remainder of this chapter refers primarily to alluvial stream/floodplain systems.

Alluvial channel reaches commonly adopt one of two basic forms, based largely on stream gradient and the character of the sediment. The first is the stream with a single, dominant channel. The **sinuosity** (i.e., the ratio between the length of the channel and the length of the corresponding valley floor) of these streams can vary widely. Although arbitrary, a sinuosity of 1.5 or greater is a good approximation of a meandering channel form. At a sinuosity of less than 1.5, a channel is considered 'straight'[19] (see **Figure 2.5**).

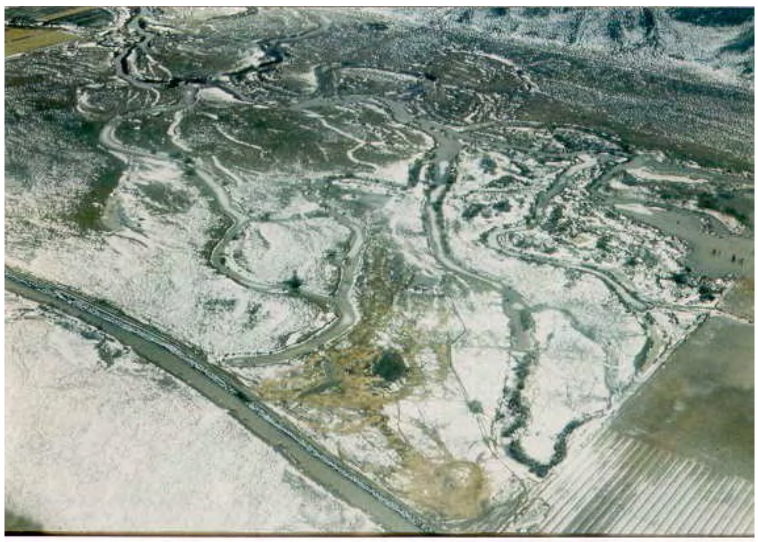
(a) Source: © 2001 Robert Glenn Ketchum (b)

Figure 2.5.
a) A high sinuosity, low gradient, fine sediment stream reach. b) A low sinuosity, high gradient, coarse sediment stream reach.

The second basic form is the **braided** stream with multiple channels active at **base flow**. The exposed areas between channels can range from unvegetated bars that mobilize during every high flow to stable, vegetated islands (see **Figure 2.6**). The channels associated with unstable bars may shift with every high flow. Although the channels associated with vegetated islands are more persistent, the relative dominance of such channels can shift frequently due to unpredictable development of log jams, usually accompanied by bedload deposition. Conditions that promote frequent channel change involve relatively steep gradient, large quantities of coarse bedload, and an abundant supply of wood.

(a) Source: T. McCoy

(b) Source: U.S.G.S.



(c) Source: Yakima Indian Nation

Figure 2.6.

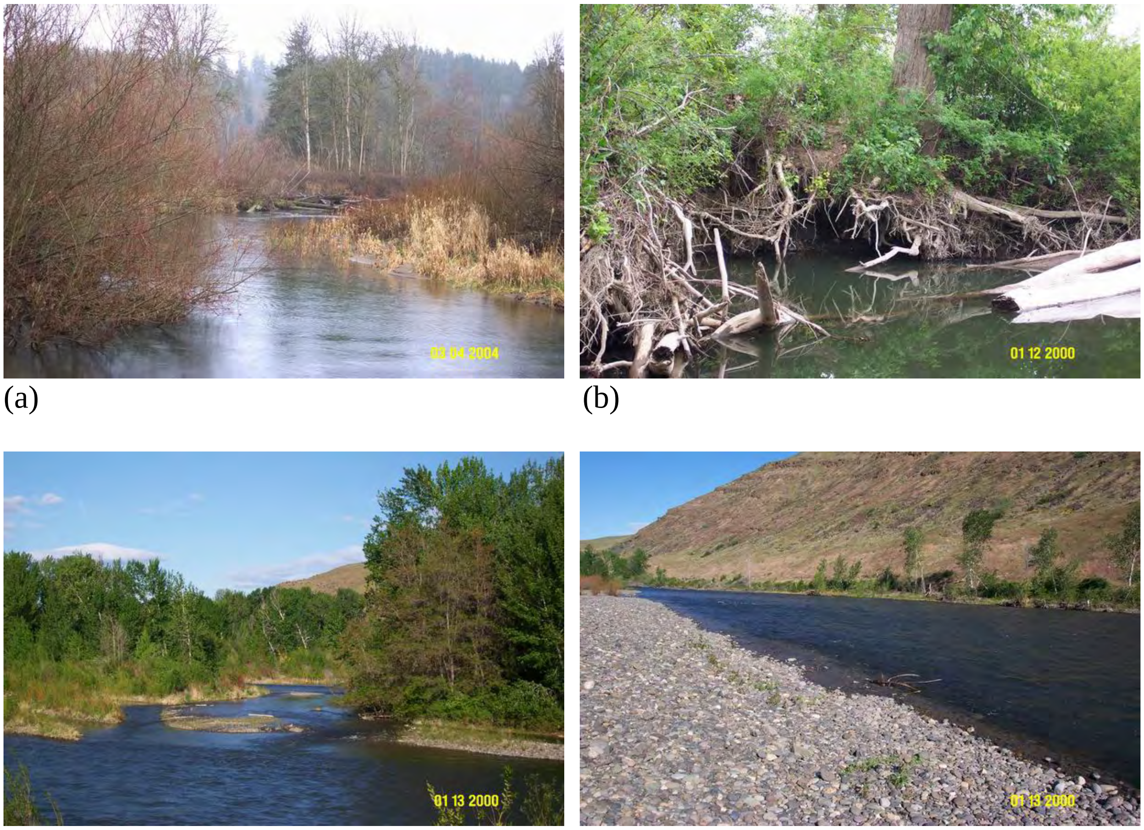
a) A braided stream with extensive unvegetated bars, indicating frequent channel change.
b) A braided stream with partially vegetated bars, indicating an intermediate level of channel stability.
c) A braided stream with vegetated islands and multiple stable channels.

Braided channels also display a wide range of sinuosity, although it is difficult to quantify. Coarse-bedded braided streams with shifting, unvegetated bars are effectively ‘straight’, while multiple, stable channels associated with low-gradient, fine sediment stream reaches tend toward higher sinuosity.

2.2.2 Stream/Floodplain Development

For the purposes of the routing and storage of water and sediment, alluvial streams and their associated floodplains comprise a single system. Under equilibrium conditions, the system is self-regulating, balancing imports and exports of water, sediment, and energy through adjustments to channel geometry. Because alluvial channels are, by definition, sculpted out of previously transported sediment, flows capable of mobilizing sediment are an essential component of channel development.

All else being equal, as depth of flow increases, velocity also increases. Furthermore, the kinetic energy of flowing water increases with the square of the velocity. Thus, swift, deep **bankfull** flows occurring during severe storms or spring **freshets** represent an extreme concentration of energy within the channel (refer to the *Hydrology* appendix for a description and definition of bankfull discharge). As water flows down slope, it must 'use up' the energy imparted to it by the force of gravity (otherwise it would accelerate indefinitely). The major mechanisms of energy dissipation are: 1) friction between the water and its channel (i.e., through surface resistance), 2) turbulence generated by channel form, such as drops over obstructions, and variations in channel cross-section and direction of flow (i.e., through form resistance), and 3) sediment transport. Generally, alluvial channels in balance with their flow and sediment loads have developed relatively 'sophisticated' means of dissipating energy. This includes a high degree of form resistance generated by complex channel geometry such as alternating pools and riffles, meander bends, mid-channel bars, and structural elements, such as large wood and beaver dams (See **Figure 2.7**). Secondly, bank stability - generated by a combination of root strength, vegetative roughness, and, in fine textured soils, soil **cohesion** - is adequate to resist flow velocities that are capable of mobilizing bed material. This allows the expenditure of energy in bedload transport. As previously noted, sediment transport through equilibrium stream reaches is balanced, thus scouring of the bed during high flow is offset by subsequent filling with sediment transported from upstream. Finally, channels in equilibrium tend to have a high degree of connectivity with their floodplains, allowing excess flood flows to spread and slow.



(a) (b)

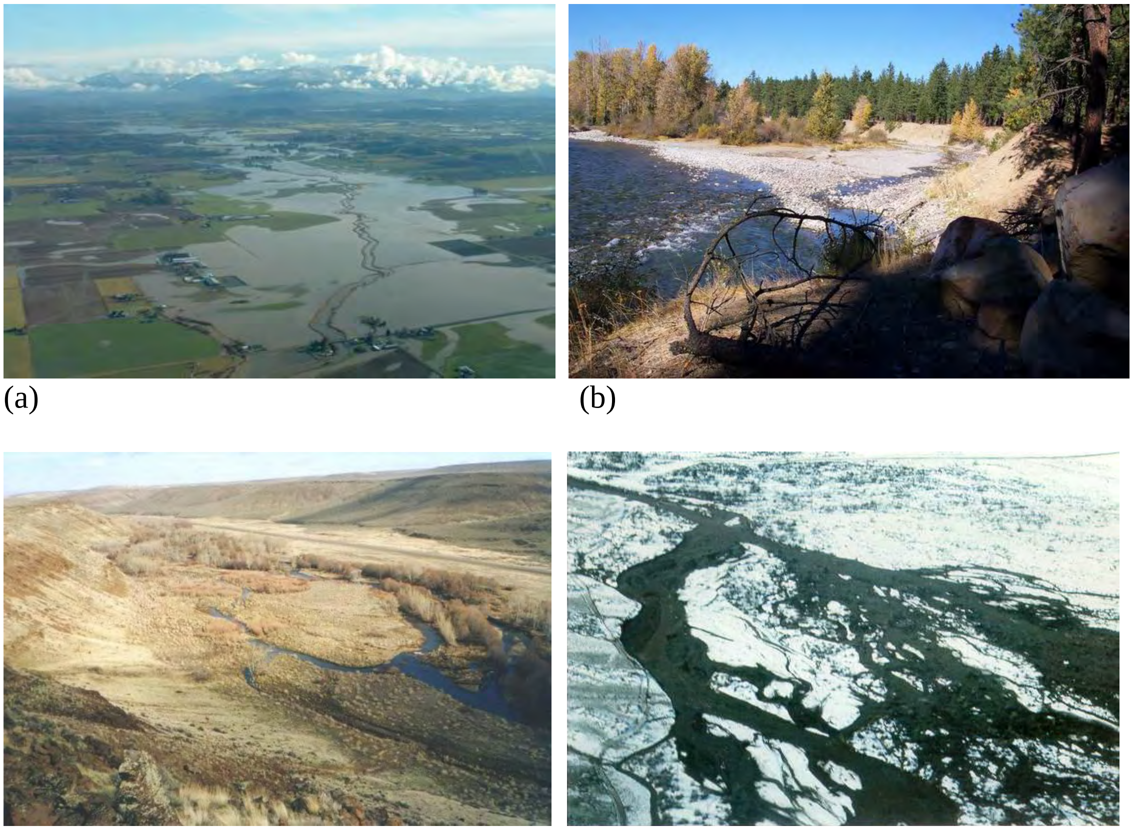
(c) (d)

Figure 2.7. a) Complexity in this stream segment includes meander and point bar development and log jams. b) Local scour creates small-scale complexity. c) Multiple channels in a high-energy stream are maintained in equilibrium by a vigorous riparian plant community. d) Simplified channel a short distance downstream of c). The constraining influences of the hill slope (shown) and a highway encroaching into the floodplain from the other side (not shown) have eliminated most of the complexity from this stream segment.

Interactions between channel and floodplain are key to the health of the aquatic ecosystem. Natural streams tend to develop channel capacities roughly equal to the peak flows occurring every 1 1/2 to 2 years. In a study of 76 streams in the Pacific Northwest, Castro and Jackson (2001)[20] observed the mean bankfull discharge recurrence interval for the Pacific Northwest to be 1.4 years (ranging from 1 to 3.1 years) (see **Figure 2.8**). Patterns varied by **ecoregion**; the humid areas of western Oregon and Washington had a mean value of 1.2 years, while the drier areas of Idaho and eastern Oregon and Washington had a mean value of 1.4 to 1.5 years.

Figure 2.8. A stream reaching bankfull flow. Source: Yakima Indian Nation

The tendency to flood during relatively minor high flow events is highly protective of the stream system; higher flows are distributed across the floodplain rather than focused in the channel. Attempts to restrict flood flows from floodplains, typically by diking or dredging, cause a great deal of stream degradation due to the increase in energy confined within the channel. It should be noted that not all floodplains are expansive, flat valley bottoms typical of large, low-gradient rivers (see **Figure 2.9**). Depending largely on valley slope and the degree of confinement imposed by the valley walls, floodplains can be relatively small and even discontinuous. In narrow valleys or canyons where the active channel occupies a significant portion of the valley bottom, the associated floodplain is a major part of the interplay between channel geometry and energy expenditure. In these systems, reduction of the available floodplain can precipitate drastic channel degradation.



(a) (b)

(c) Source: Yakima Indian Nation (d) Source: Yakima Indian Nation

Figure 2.9. a) A broad, relatively flat floodplain. b) A combination of low, vegetated floodplain, exposed bars, and high flow channels provide flood capacity. A high terrace bounds the floodplain. c) Multiple high flow channels provide flood relief for moderate floods. d) Distributary channels convey flood flows on an alluvial fan.

Two fundamental processes, lateral and vertical accretion, create floodplains. Lateral accretion consists of the deposition of sediment on **point bars**. As erosion occurs along the **cut bank** of a **meander bend**, the bed material derived from this erosion generally transports down the same side of the channel to the next submerged point bar. This process tends to balance erosion from the cut bank on the outside of a meander bend with accretion on the opposing point bar, maintaining channel width and elevation throughout the progression of **meander migration** (See **Figure 2.10**). When meandering streams are in equilibrium, point bar crests approach the elevation of the floodplain. Conversely, point bar development that does not crest near the level of the floodplain is symptomatic of an incising and degrading channel. Under equilibrium conditions, lateral accretion does not add to, or subtract from, the area or height of the floodplain.

Figure 2.10. A formerly straightened channel reestablishes a meander pattern.
Source: Yakima Indian Nation

Vertical accretion is caused by floodwaters carrying sediment out of the channel and depositing it on the floodplain (see **Figure 2.11**). Thus, vertical accretion is responsible for building valley bottoms. The quantity and quality of deposited sediment relates to the energy of the floodwater carrying sediment out of the channel, and the degree to which floodwaters are slowed by the floodplain.

(a) Source: Yakima Indian Nation

(b)

Figure 2.11 a) Lateral accretion: sand and silt deposited on the point bar of the meander shown in **Figure 2.10**. b) Vertical accretion: fine sediment captured on a floodplain.

Avulsion, or an abrupt change in the alignment of a channel, occurs when floodwaters carve a new course across the floodplain. As with other instances of erosion, this is a natural part of channel evolution that can also be accelerated by human activities. Chute-cutoff, the most regular and predictable form of avulsion, is a result of channel lengthening through meander development. The paired processes of cut bank erosion and point bar development cause progressive channel lengthening and a corresponding decrease in gradient. Eventually, the stream's ability to transport sediment is reduced, leading to deposition and a loss of channel capacity. As channel capacity declines, the floodplain conveys correspondingly greater flows. These flows are conveyed straight down the valley gradient, rather than along the sinuous course of the channel. When the velocity of flows conveyed down the floodplain overcomes the shear strength of the floodplain surface, a new, shorter, higher gradient channel is eroded that cuts off the old meander. This process is the origin of oxbow lakes (see **Figure 2.12**).

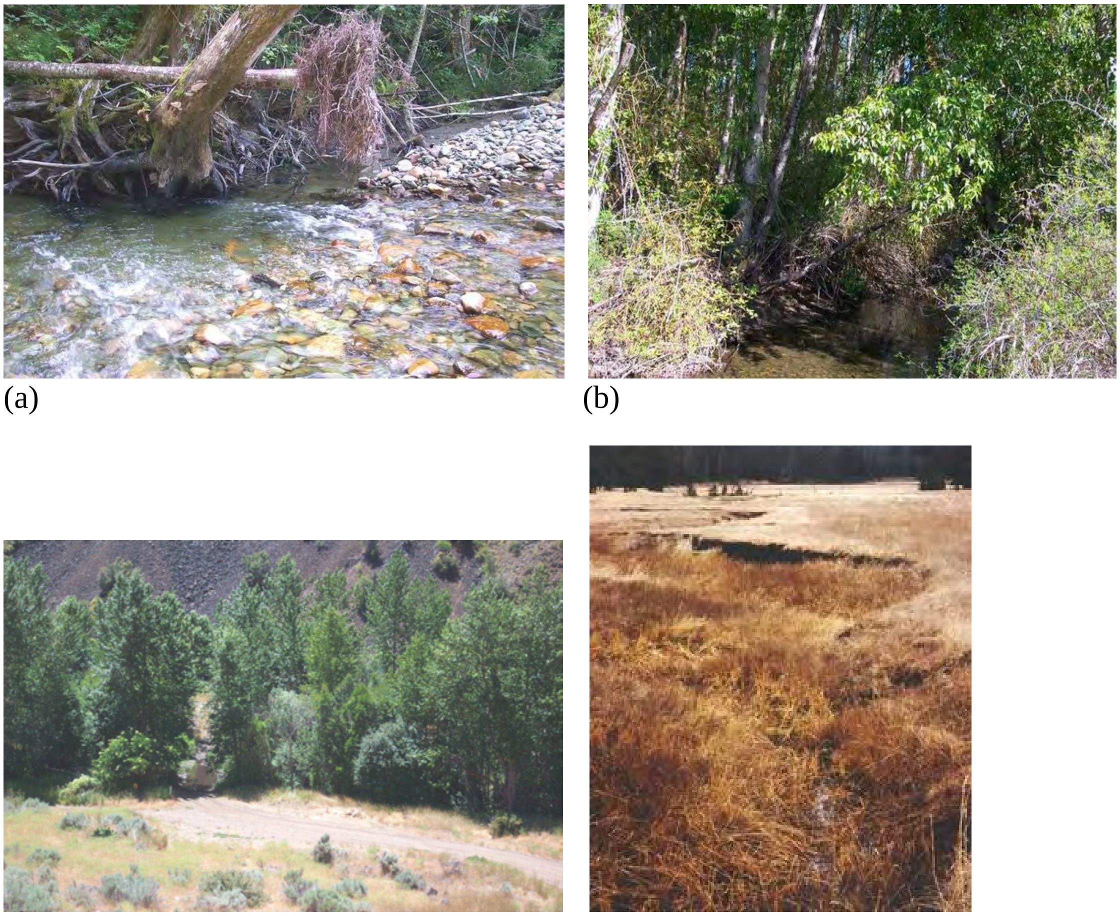
Figure 2.12. Oxbow lakes resulting from meander cutoff.
Source: U.S.G.S.

Less predictable, and normally associated with major floods, is a major re-routing of the channel across the floodplain. Again, the erosive energy of the flood flows must be greater than the resistance of the floodplain to erosion for avulsion to occur. Conditions that promote avulsion include reduced channel capacity, devegetation of the floodplain, and an incised channel at the downstream location where flood flows return to the channel. Reduced channel capacity obviously causes more overbank flow; devegetation reduces the floodplain's ability to resist erosion and an incised channel at the point where flood flows return allows for the initiation of **headcutting**. Headcutting is erosion, progressing in the upstream direction, of the streambed. It occurs when a portion of the bed is too steep to remain stable under the flow conditions to which it is subjected. Where the slope of the bed is only moderately oversteepened, the shear forces imposed by high velocity flow erode the bed material. Where there is a vertical, or near-vertical discontinuity in the streambed, the turbulence created by the plunging water undercuts the vertical face. Waterfalls are the most dramatic forms of vertical headcuts. Flood flows returning to an incised channel create short-term waterfalls. When this occurs, the bank material is rarely fully resistant to the erosive forces; a headcut is initiated that works upstream toward the source of the overbank flow (see **Figure 2.13**). If the flood duration is sufficient to allow the headcut to work upstream to the main channel, a complete channel avulsion is a possible outcome. However, headcutting is also responsible for the development of complex features in well-vegetated floodplains, including side-channels, backwater channels, and springbrooks.

(a) (b) Source: Yakima Indian Nation

Figure 2.13. a) Headcut created through basalt bedrock by the Missoula floods. b) Headcut from floodwaters returning to the stream channel. The conversion from woody riparian vegetation to row crops has drastically reduced both floodplain surface roughness (increasing flood flow velocity and shear force) and strength (reducing its resistance to erosion).

The strength and roughness provided by vegetation in riparian areas is crucial to stream/floodplain development and functioning. The roots of streamside vegetation provide strength to the soil mass, greatly increasing bank stability. Roots protruding from banks also create roughness that lessens near-bank flow velocities and erosiveness. In combination, these attributes allow the development of complex channels (e.g., deep, narrow, and sinuous, with undercut banks) having comparatively limited capacity and frequent overbank flows (see **Figure 2.14**).



(a) (b) (c) (d) Source: Yakima Indian Nation

Figure 2.14. a) An undercut bank maintained by woody riparian vegetation. b) Multiple layers and species of riparian vegetation. c) A narrow riparian corridor typical of a small stream in a semi-arid setting. d) A rush and sedge riparian community in a recovering (i.e., aggrading) system. Previous overgrazing caused channel incision.

Floodplain vegetation slows overbank flows, reducing erosion and promoting the capture and stabilization of fine sediments. The development of relatively fine-textured soils in turn supports increasingly dense and vigorous riparian vegetation. The deep soil developed by sediment deposition provides near-stream soil-water reservoirs (i.e., ***bank storage***) that are recharged during flooding (further damping flood peaks). During dry periods, clean, cool water stored in near-stream soils return to the channels, contributing in both quantity and quality to ecologically critical base flows.

2.2.3 Hyporheic Flow

The hyporheic zone is the volume of saturated sediment beneath and beside streams where ground water and surface water mix. Hyporheic flow (i.e., water flowing in near-stream sediments that can freely mix with surface flow) occurs effectively only in relatively coarse-textured sediments and under flow conditions with enough stream **gradient** to drive flow through the available pore spaces. The hydraulic conductivity of the hyporheic zone increases with sediment size and the degree of sorting of particle sizes (sorting of particle sizes is another product of structural and hydraulic complexity). Fine sediment can effectively seal the pores of the streambed and drastically reduce hyporheic flow. Thus, land uses that increase fine sediment inputs to streams, particularly during low flow periods, can impair hyporheic functioning.

Hyporheic flow operates at various scales. On a valley scale, flows **downwell** into relatively deep **alluvium** downstream of transitions from shallow to deep bedrock, and **upwell** upon reaching the next shallow groundwater obstruction. Flow paths can be long and relatively deep, and are often concentrated in buried former channel courses known as **paleochannels** [21].

Reach-scale hyporheic flow is generally driven by variations in depth to the **water table**. Where the water table is above the water surface in the stream, an upwelling zone occurs, and hyporheic flow is delivered to the channel. Where the water table is below the water surface in the stream, a downwelling zone occurs, with some streamflow penetrating the bed and bank and becoming hyporheic flow. Because the depth to the water table can fluctuate seasonally, upwelling and downwelling zones may also seasonally expand and contract along the length of the channel. Typically, the water table gradually rises throughout the high runoff period, particularly during flooding, and falls after the peak seasonal flows. Extreme downwelling occurs where the water table is far below the channel and the alluvium is coarse. For example, steep canyon streams discharging onto coarse alluvial fans commonly are strongly downwelling through the upper portion of the fan. In extreme cases, a stream reach can be so strongly downwelling that there is virtually no lateral seepage from the stream and a hole dug a few feet from the water's edge will remain dry.

Near-stream vegetation is sometimes an indicator of reach-scale hyporheic functioning, particularly in more arid environments. Due to the depth to the water table during the growing season, strongly downwelling zones may support no more than sparse riparian vegetation, or even upland vegetation, on the streambanks. Because these sites are not conducive to revegetation, evaluating whether this is a cause of apparent riparian degradation can be critical to developing recovery or restoration plans. Conversely, due to the sustained accessibility of a shallow water table, degraded riparian vegetation associated with upwelling reaches may require no more than improved management to achieve rapid recovery.

Smaller-scale hyporheic flow occurs in response to variations in the streambed. Flow penetrates the streambed gravels where the channel is decreasing in depth, such as at the **tailout** of pools, and travels through the bed along shallow flow paths that are intercepted at the next deepening of the channel, such as the upstream end of the next pool[22].

The distribution and extent of hyporheic zones depend upon the volume and texture of sediment underlying the channel and floodplain. In many cases the hyporheic zone is of limited extent, but in some settings, such as broad alluvial valleys comprised of permeable gravel, the hyporheic zone can be quite extensive[23]. For a more thorough discussion of hyporheic flow, refer to the *Hydrology* appendix and Edwards (1998).

2.2.4 Influence of Large Wood on Stream Morphology

Forested alluvial streams are often heavily dependent on physical interactions with large wood for channel development and stability. In addition to live trees stabilizing stream banks, large wood frequently exerts a major influence on stream channels[24]. Stream cleaning (i.e., the removal of large wood) has been one of the most destructive practices for aquatic habitat. For example, numerous coastal streams drain watersheds underlain by sandstone. With sediment loads largely consisting of sand-sized material, alluvial streams are heavily dependent on large wood to capture and retain sediment. Typically, when 'cleaned' of large wood, these streams quickly erode their bed until reaching bedrock. This represents a drastic change in stream processes and aquatic habitat.

The function of large wood changes in the downstream direction, as the ratio between the length of available large wood and channel width decreases. Where channel width is less than the length of the elements of large wood, individual pieces are able to span the channel. Over the course of time, channel-spanning large wood may be incorporated into the streambed, creating natural drop structures that 'stair-step' the streambed (see **Figure 2.15**). In effect, the stair stepping creates **channel units** with lower gradient conditions than the overall stream gradient. Energy dissipation and sediment transport are greatly affected by these natural structures; finer bed material is captured in the backwaters of these structures and plunging flow scours pools downstream. Energy dissipated in the plunge is then unavailable for erosion and sediment transport [25].

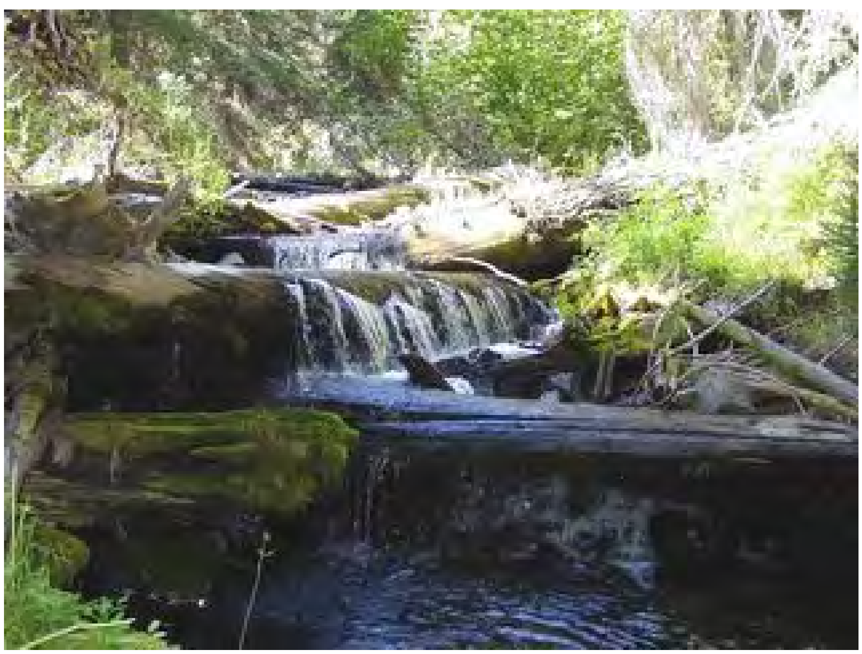


Figure 2.15. Natural large wood drop structure. Source: Yakima Indian Nation

In larger streams, where the length of the available large wood is less than channel width, the wood is apt to be mobilized at high flows. Large pieces, anchored by a heavy **rootwad** or, lodged on an obstruction, tend to collect floating wood, leading, in time, to structurally distinctive log jams[26] (see **Figure 2.16**) with tremendous habitat value. These jams generate complex local hydraulics, creating low-velocity depositional areas and high-velocity areas subject to **scour**. Their influence may promote side channel, point bar, or island development, and increase **avulsion**[17 26].

(a)

(b)

(d)

(e) Source: Paul Bakke

Figure 2.16. a) Channel-spanning log jam. b) Log jam accumulated along the bank. The key piece in this jam is a large tree that toppled into the stream while remaining rooted in the bank. c) Wood accumulated along the outside of a bend in a high-energy system. Spanning pieces have minimal interaction with the flow. d) A log jam that has formed on a low bar outside of the low flow channel. This jam interacts with moderate and higher levels of flow. Note the plume of sand that has accumulated in the 'lee' downstream of the jam.

Irrespective of channel width, trees falling directly into the channel from the banks (as contrasted with those delivered from the uplands by mass-wasting) often are anchored to the bank by roots. Depending on the orientation of the trunk, the tree may provide protection to the bank by reducing flow velocities. Conversely, it may cause bank erosion by directing flow toward the bank or by causing an eddy. Although large wood has the potential to increase local erosion, on the larger scale it reduces erosion by dissipating energy.

The species of trees available to the stream has a strong influence on the interactions between wood and the channel. Tree size is an obvious factor influenced by species, the larger the wood, the greater its ability to physically affect the stream. Buoyancy, which differs among tree species, also relates to the behavior of large wood when it enters the stream. Low-density wood, such as spruce or western red cedar is more readily floated than higher-density wood such as Douglas fir. Over the course of time, waterlogging increases the density and stability of large wood in the channel.

Another significant variable is the longevity in the stream environment of large wood. Old-growth conifers such as western red cedar and Douglas fir, noted for their resistance to decomposition, can persist in streambeds for hundreds of years, contributing to long-term stability. At the other extreme, Big Leaf maple, a riparian hardwood common in the stream corridors of western Washington and Oregon, although achieving a large size, decomposes quickly unless continuously submerged, and so rarely has a lasting influence on the stream.

Another factor involves the typical characteristics of large wood pieces that are delivered to the channel. Some tree species tend to remain relatively intact as they fall; others tend to shatter. In systems where the available trees tend to shatter, the formation of channel-spanning steps is limited to relatively small channels, whereas the greater quantities of mid-sized and finer material promotes formation of various log jams and accumulations. These typically develop around key pieces in the channel, at the heads of high flow channels, along the outside of meander bends, on point bars, and on floodplains. Western hemlock, a common late-succession conifer species in the maritime Northwest with an increasing tendency to shatter as it ages, commonly delivers segments of trunk to stream channels[27]. Cottonwood, the dominant riparian tree throughout much of the inter-mountain west, is large but relatively short-lived. Although the trunks of cottonwood trees are often delivered intact to the stream, the tops tend to break, producing substantial quantities of smaller wood. Thus, log jams in these systems, while often developing on large key pieces, are typically relatively dense, due to the accumulation of finer material.

As previously noted, large wood can be a key component in maintaining channel stability and structure in forested watersheds. Variations in the quantity and quality of wood naturally available to streams are significant for energy expenditure, erosion, deposition, channel geometry, and the tendency to avulse. As with the other stream system components, the characteristics of the natural supply of wood should be considered when restoration plans are formulated.

2.2.5 Influence of Beaver Activity on Stream Morphology

Beavers have exerted a significant influence on the development and form of many small- to medium-sized stream systems. In semi-arid regions, where large riparian trees are naturally lacking along many small streams, beaver dams may play a role as significant as that of large wood in forested streams. Similarities in physical function include: flattening of local stream gradients, increasing interactions between the stream and floodplain, increasing bank storage, capturing of relatively fine sediment in the channel, pool formation, and hyporheic exchange. Beaver dams represent structural elements within stream channels (see **Figure 2.17**). In some cases, the strength and energy dissipation provided by these structures is an essential element of the stream's equilibrium. Removal of beaver from these systems can have the same drastic consequences as the removal of large wood from forested streams.

(a) (b)

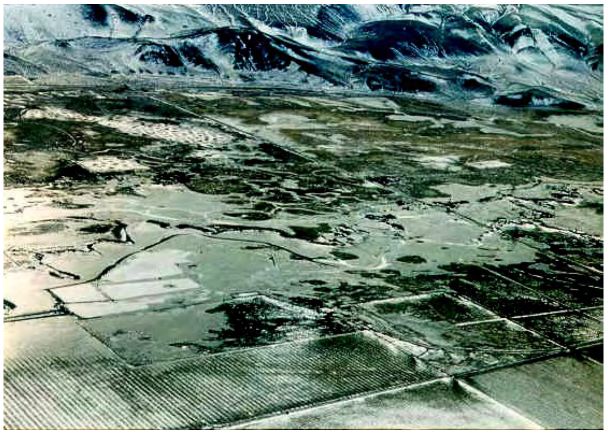
Figure 2.17. a) West-side beaver pond. b) East-side beaver pond.

In larger stream systems, beaver activity is principally limited to side channels and floodplain features. Although the direct effects of their activities on the stream are reduced as stream size increases, indirect effects on stream processes can still be significant through influences upon the riparian plant community. Herbivory by beaver, especially on dominant species of trees, affects both structure and composition of the plant community. Furthermore, beaver ponds affect both floodplain soil development, through sediment capture, and soil chemistry, by promoting saturated conditions, again influencing the plant community.

2.2.6 Disturbance and Stream Processes

Natural Disturbance

Stream corridors are the most dynamic, frequently disturbed component of the landscape. To a degree even greater than in the surrounding uplands, the disturbance regime drives ecosystem structure and function. Primary among the disturbance factors is flooding. The energy inherent in high flows does the work of shaping the channel and floodplain, maintaining channel capacity, and transporting and depositing sediment (see **Figure 2.18**). Flooding serves as the principal mechanism for creating, maintaining, and destroying channel and floodplain features such as pools, islands, bars, oxbows, side channels, and off-channel ponds.



(a) Source: Yakima Indian Nation

(b) Source: Yakima Indian Nation

(c)

Figure 2.18. a) Extensive flooding in a low-gradient system. b) High flows generated by a rain-on-snow event. c) Flood damage. Excessive coarse sediment deposition is usually not associated with proper floodplain functioning.

Other disturbance factors commonly affecting stream corridors include: mass-wasting (i.e., landslides and debris torrents), fire, drought, ice jams, severe wind, and insect and disease outbreaks. Each disturbance factor has the potential to affect the riparian plant community, thereby affecting strength and roughness characteristics of the stream corridor. Some, such as mass-wasting and ice jams, have the potential to mechanically alter stream channels.

Channel-altering disturbance may cause a temporary loss of the dynamic equilibrium in channel geometry and sediment transport described in the previous section. Following such disturbance, streams typically undergo a period of recovery during which equilibrium channel geometry reestablishes. For example, channels that straighten and widen in the course of a large flood, through the processes of revegetation and sediment capture, will gradually narrow and regain sinuosity. Equilibrium, once reestablished, then persists until the next channel-altering event.

Some disturbances are so severe, or chronic, that the energy dissipation characteristics of the channel/floodplain system undergo a long-term alteration. For example, disturbance that removes natural structure from a stream channel (e.g., channel scouring following the breaking of a debris dam, stream cleaning, or beaver dam removal) may trigger channel incision and a long-term loss of floodplain connection.

The frequency of channel-changing disturbance, rate of recovery, and therefore the proportion of time the stream system persists in equilibrium vary among ecosystems. Climate plays a dominant role in the occurrence, magnitude, and frequency of most disturbance factors. It also has a major influence on the rate of stream recovery between disturbances. Generally, the relative fluctuation between high and low flows in a stream system is inversely proportional to average annual precipitation. With increasing aridity, stream systems are subject to increasingly extreme flow fluctuations. In the semi-arid regions of the interior Pacific Northwest, the combination of comparatively 'flashy' flow with rapid runoff and low baseflow- and relatively unfavorable conditions for revegetation results in rather slow recovery following disturbance. Recovery from major disturbances may be measured in decades in these systems. Conversely, streams in the humid, temperate maritime regions are generally more resilient and quicker to recover. **Figure 2.19** provides examples of base flows in different systems.

(a) Source: Paul Bakke (b)

Figure 2.19. a) Typical small, humid-system stream at base flow. b) Typical semi-arid system stream at base flow.

<u>Human-Caused Disturbance</u>

A range of human activities, have the potential to alter the disturbance regimes of stream systems. Alterations to the storage and delivery of water, sediment, or large wood from the uplands tend to occur synergistically rather than independently, and can result in substantial cumulative effects. For instance, widespread soil compaction results in loss of soil moisture storage, affecting the vegetative community, runoff patterns (i.e., increasing peak flows and decreasing base flows), and erosion. Similarly, changes to the vegetative community affect water use, soil stability, and possibly the supply of large wood.

Human activities within stream corridors involve direct disturbance to channels through manipulation (e.g., diking, filling, straightening, bank armoring, and wood removal), and indirect disturbance through changing streambank and floodplain characteristics (e.g., reducing the strength and roughness of the banks and floodplain by converting from native vegetation to agricultural crops.). See **Figure 2.20** for examples of direct and indirect channel disturbance.


(a)


(b)

Figure 2.20. a) Channel straightening. b) Floodplain converted from native vegetation to pasture

As previously discussed, stream/floodplain systems in dynamic equilibrium have 'adapted' to their particular supplies of water, sediment, and structural elements. Human-caused disturbances generally disrupt, to some degree the processes governing the delivery of these supplies.

2.2.7 Climate Change and Stream Processes

Climate is a fundamental driver of ecosystems at all scales from landscape-level to microsites inhabited by individual plants. Not only does climate directly dictate the mix of species that can inhabit a landscape, it does so indirectly through its dominant role in the disturbance regime. Climate change is both natural and inevitable. Its effect on ecosystems is a product of the magnitude and rate of change. The least determinate but most profound disruption to watershed and stream functioning caused by human activities are the potential effects of significant, rapid, human-caused climate change.

Climate change inevitably leads to ecosystem change. Stream systems will be directly affected through changes in the amount and timing of streamflow and sediment yield, and indirectly through changes to the plant communities. Many drainage systems show evidence of previous climate change. For example, high **terraces** composed of alluvial materials (indicating a lowering of the base level of the stream system), are often relics of an earlier climatic period. Stream channels are continually adjusting to climatic inputs. Channels in equilibrium make minor adjustments in response to individual channel-forming events. Climate change that modifies the natural range of variability will alter channel characteristics, sometimes to the extent of completely changing the channel type (e.g., from single thread and sinuous to braided).

Of particular significance to many streams in the Pacific Northwest are the implications of changes, due to global warming, in the accumulation and distribution of snow packs. Even assuming that precipitation patterns remain the same, reductions in the quantity of water temporarily stored in snow packs will translate into higher, earlier annual peak flows and longer, lower base flows, i.e., more severe flooding and drought.

2.2.8 Channel Degradation and Recovery

Channel degradation (i.e., simplification) occurs due to cumulative effects, local disturbance, or a combination of both. Cumulative effects can be difficult to identify, particularly when they are superimposed upon local disturbance. Recognizing the underlying causes of degradation often requires expert interpretation of existing conditions and historical information. Similarly important, and also requiring substantial expertise, is the identification of trend in channel condition. Degraded channels can be grouped into three categories, based on trend: 1) those that are actively undergoing degradation, 2) those that are degraded but stable, and 3) those that are recovering. Long-term familiarity with the system involved is extremely valuable in accurately identifying channel condition and trend.

The concept of a *threshold of stability* may be useful when thinking about channel degradation. Until a threshold is reached, small changes in the factors driving a system cause small responses by the system. When the threshold is reached, a small change in the driving factors elicits a major change in the system. For example, progressive encroachment into a broad floodplain that precludes flooding correspondingly increases the depth and velocity of flood flows throughout the remaining floodplain and in the channel. This may result in little observable channel change until in-channel velocities increase to a degree that the stream banks or bed are no longer stable. As that threshold is exceeded, rapid change may occur that drastically alters channel characteristics. Essentially, the channel is adjusting the balance among the different mechanisms of energy dissipation, and the adjustment period corresponds to the early stages of the ‘actively degrading’ trend mentioned above (see **Figure 2.21**).

Figure 2.21. A widening channel. Much of the channel has cut down to bedrock, leaving little opportunity to expend energy transporting bedload. Hence, the erosive energy of high flows is expended on the banks, which have destabilized.

In contrast to complex stream systems with variable geometry, structural elements (e.g., wood and boulders), and a high degree of connectivity with their floodplains, degraded streams that are comparatively simple in plan, cross-section, and profile expend energy in relatively 'crude' ways. Energy dissipation in degraded streams is generally dominated by surface resistance and/or excessive erosion and deposition. Surface resistance increases as the channel widens and flows become shallower. Additionally, it is increased by coarsening of the bed material. Unbalanced sediment transport (i.e., erosion and deposition) is characterized by channel downcutting, where bed materials are more easily eroded than the banks, and by widening, accompanied by unstable mid-channel bars, in coarse-bedded stream segments.

Degraded but stable streams have completed their adjustment to a new balance of energy dissipation, but, similar to terrestrial desertification, they lack recovery pathways to their former state. Or, the rate of recovery is too gradual to be meaningful for our purposes. Degraded but stable streams generally have lost the ability to capture and stabilize fine sediment (see **Figure 2.22**). Examples include channels that have eroded to bedrock and developed a width just sufficient to transport available water and sediment; and coarse-bedded streams that have straightened and widened, through bank erosion, to such a degree that high flows are retained within the banks and stabilizing perennial vegetation is continually scoured.

Figure 2.22. A channelized stream that is in a degraded but stable condition.
Source: Paul Bakke

Degraded but recovering streams are often recognizable by the establishment of young perennial riparian vegetation appropriate to the site. Pioneer species colonizing bars are often the first sign that recovery processes are underway, although in order to ‘count’, vegetation must have survived through at least one high flow period. If persistent through high flow conditions, these pioneers create zones of reduced flow velocity, promoting deposition of finer sediment. Such sediment capture is key to initiating succession of riparian plant species.

Under most circumstances, a vigorous riparian plant community, being the means to stabilize sediment, is key to natural channel recovery and long-term stability; it is always necessary, and often sufficient. Where cumulative effects are causing degradation, however, the native plant community may not be adequate to maintain stability; in these circumstances, off-site practices must be altered before recovery can proceed.

It should be emphasized that a vigorous plant community includes a range of age classes. Often, when site conditions change, the established vegetation remains healthy, but the conditions necessary for propagation have been eliminated. Thus, the community ages and eventually declines if proper site conditions are not reestablished. The long-term implications for stream stability are serious. A well-known example is the decline in cottonwoods in many western stream corridors. Cottonwoods rely on floodwaters to distribute their seeds onto freshly deposited sediments. They are adapted to synchronize release of their short-lived seeds with the peak spring runoff period. River regulation and loss of floodplain connection has drastically reduced the recruitment opportunities for cottonwoods along many western streams. Excessive grazing can also inhibit regeneration. Large, old cottonwoods persist along many streambanks where there are no young cottonwoods to be seen. **Figure 2.23** contrasts vigorous and decadent cottonwood communities.

(a) (b)

Figure 2.23. a) A vigorous cottonwood-dominated riparian community with various age classes represented. b) A decadent cottonwood community on a stranded floodplain. It has been many years since regeneration occurred at this location.

2.3 Stream Habitat

Stream ecosystems extend well beyond the channel, taking in the entire stream corridor. The stream corridor is comprised of the stream channel, its shoreline, the **hyporheic zone**, and the surrounding floodplain and **riparian area,** encompassing and connecting both aquatic and terrestrial habitat. As previously noted, stream corridors are frequently disturbed. Aquatic ecosystems and their constituent organisms have evolved accordingly – with high system resilience (i.e., ability to recover from **disturbance**) and a variety of adaptations that enable organisms to survive the tremendous range of conditions occurring annually and episodically. These adaptations generally capitalize on key attributes of stream ecosystems, such as habitat complexity, and connectivity. Note that, because ecosystems are dynamic in space and time, suitable habitat will not be available to all species in all streams at all times.

2.3.1 Habitat Complexity

A fundamental characteristic of ecosystems is that biological complexity (i.e., diversity) requires habitat complexity. In the case of aquatic ecosystems, features such as channel structure, bed material, flow velocity, water quality, temperature, and nutrient availability influence **biotic** diversity[28 29 30]. Structural complexity creates an array of microhabitats that provide for the needs of an assortment of species throughout their various life stages. Conversely, community diversity in streams with simple habitat is lower than in those with higher habitat complexity[31].

The frequency and magnitude of floods is the primary driver of structural complexity within stream corridors, periodically creating and destroying the various features within the channel and floodplain. Complex channel/floodplain structures generate hydraulic complexity (i.e., varying flow velocity, depth, and turbulence) throughout a range of flow conditions (see **Figure 2.24**). This is critical to meeting the diverse needs of aquatic organisms through all life stages. Complex hydraulics, interacting with sediment and vegetation (including roots and large wood), create and maintain ecosystem structure.

Effectively, structural complexity, hydraulic complexity and high quality habitat are related characteristics of a properly functioning stream/floodplain system.

Figure 2.24. High quality aquatic habitat is the result of structural and hydraulic complexity.

2.3.2 Habitat Connectivity

Although connectivity within the stream corridor is most obviously essential for salmonids and other migratory fishes, it is also of critical importance to a host of non-migratory aquatic organisms. Individual responses to varying flow conditions and the need for food, shelter, and reproduction typically include movement up and downstream (i.e., longitudinally), up and down through the water column, and even into the porous streambed (i.e., vertically), and from the middle of the channel to the margins and off-channel floodplain features (i.e., laterally). The timing and direction of movement, and distance traveled vary with the species, age, and specific needs of the individual.

Longitudinal Connectivity

An obvious characteristic of stream/floodplain systems is longitudinal connectivity across the landscape (originating near watershed divides and generally terminating at the ocean). The ecological implications of this connectivity are profound. In addition to storing and routing matter in the downstream direction, these systems provide continuous habitat and migration corridors essential to many aquatic and terrestrial species.

Longitudinal connectivity is vital to ecosystem resilience: the ability to recolonize sites after severe disturbance. Generally, small- to medium-sized, high-gradient streams are subject to infrequent but severe disturbance (*sensu*, Benda et al. 1998) that can eliminate much of the aquatic and riparian life within a stream reach. This most commonly is caused by multiple disturbances, such as when a high intensity rain or snowmelt event occurs several years after fire, clearcutting or road construction. The combination of reduced root strength and soil saturation may trigger landsliding and debris torrents capable of scouring and damming channels. It should be noted that extremely infrequent and severe events might affect even relatively large streams, such as in 1980 when the Toutle River was overwhelmed by mud and debris flows triggered by the eruption of Mt St. Helens. Connectivity within the system is key to re-colonizing these sites following severe disturbance[32]. When habitat connectivity is lost, migratory species may be excluded, and disturbance can lead to local extinction of resident species (see **Figure 2.25**).

Figure 2.25. a) Natural fish passage barrier. b) Human-created fish passage barrier.

Lateral Connectivity
The lateral dimension of the stream corridor runs perpendicular to flow. Streams have a lateral structure that begins at the main channel and progresses through the channel margin and floodplain/riparian habitats to the adjacent upland environment. Riparian/ floodplain habitats may consist of side channels, off-channel ponds and wetlands, perennial or intermittent streams and springs, and periodically flooded grasslands and forests. These riparian/floodplain habitats offer feeding, reproduction, and refuge habitat for invertebrates, fish, amphibians, reptiles, birds, and mammals. Flooding provides periodic or episodic surface connection between the various floodplain features and the active channel, allowing the exchange of organisms and materials (e.g., wood, sediment, solutes). **Figure 2.26** illustrates the simplification caused by diking.

Figure 2.26. Dikes have been used throughout history to disconnect channels from their floodplains.

Vertical Connectivity: the Channel and Hyporheic Zone
The vertical connectivity of in-stream habitat refers to the physical, chemical, and biological interconnectedness of the water column in the channel and throughout the hyporheic zone. As noted in the Section 2.2.4 *Influence of Large Wood on Stream Morphology* the hyporheic zone is the volume of saturated sediment beneath and beside streams where ground water and surface water mix.

Recognition of the hyporheic zone and its importance is relatively recent and much is still poorly understood. According to a literature search by Edwards, the ecological significance of hyporheic zones includes:

- Affecting surface water quality,
- Influencing the retention and processing of solutes,
- Contributing to the decomposition of organics,
- Providing habitat to diverse and abundant organisms and serving as refuge, buffering organisms from disturbance in discharge and food supply, and
- Providing one of the dominant links between the riparian zone and the stream channel.

Geomorphic and hydrologic processes within a watershed result in a systematic distribution of sediment within the stream system. These processes dictate the location, quantity and quality of sediment deposits, ultimately controlling the occurrence and degree of hyporheic functioning. The ecology of gravel-bedded streams appears to be heavily influenced by hyporheic functioning.

2.3.3 Flooding, Stream Habitat and Stream Ecology

Flooding is an essential ecological interaction between the river channel and its associated floodplain[33]. Flooding creates, maintains, modifies and destroys physical floodplain features such as bars, levees, swales, oxbows, backwaters, and side channels; floodwaters carry sediment, organic material, nutrients, and biota to and from the floodplain; flowing water sorts sediments, creating floodplain soils that are stratified both vertically and horizontally. Varied floodplain topography creates a gradient of depth and duration of flooding. Every plant has an optimal position along this gradient. This gradient, coupled with variations in soil structure, vegetation, and topography create a complex and dynamic network of habitats throughout the floodplain .

Floodplains alternate between aquatic and terrestrial environments and the change can be stressful, or even detrimental, to the affected biota. Organisms may be killed or harmed during the flood event (e.g., drowning, scouring of eggs from redds) or they may be affected by the resulting change in habitat conditions immediately following the disturbance and during the system's recovery. The biological response of biota to the dynamic floodplain environment varies with the regularity, frequency, and duration of inundation, the rate of change, the abundance and distribution of new and undisturbed habitat, and the abundance, distribution, sensitivity and adaptive capability of the surviving populations. Headwater streams are characterized by rapid, unpredictable changes in flow, as their hydrology is strongly influenced by precipitation events. In contrast, large streams and rivers with access to extensive floodplains typically have a more predictable flooding regime.

The intermediate disturbance hypothesis predicts that biotic diversity will be greatest in systems that experience moderate levels of disturbance[34]. Disturbances that are too frequent or too intense are thought to suppress biotic diversity by causing local extinction of certain species and/or dominance of colonizing species[35 36]. In systems subject to infrequent disturbance, competitive interaction of species becomes the dominant force determining the structure of biological communities; superior competitors tend to dominate. Some moderate level of disturbance allows colonizing species to coexist with superior competitors, as neither species is favored.

2.4 Summary

Channel and floodplain structure, and by extension, aquatic habitat, are created, maintained, and destroyed by the energy inherent in high flows. Energy is expended through erosion, sediment transport, and various forms of friction. Critical to stream channel characteristics are the proportions of the different types of energy dissipation. These are the result of interactions among streamflow, sediment quality and quantity, channel and floodplain geometry, stream corridor vegetation, and structural elements. Complex patterns of sediment erosion and deposition, created by these interactions, underlie diverse, productive aquatic and riparian habitat.

A stream reach in dynamic equilibrium has developed a geometry that balances the energy available for sediment transport with the supply of sediment being delivered to the reach. This does not imply that sediment transports through the reach without stopping.

Rather, it indicates a balance between erosion and deposition. With balanced rates of erosion and deposition, individual channel and floodplain features are created and destroyed but overall channel characteristics such as sinuosity, gradient, width/depth relationships, and pool and riffle frequency are maintained. The stabilizing role of vegetation in channel development and maintenance cannot be overemphasized. Channel complexity, having a large effect on energy dissipation, exerts a major influence on erosion, sediment transport, and deposition. Thus, complexity is intimately intertwined with maintenance of a dynamic equilibrium.

A stream reach undergoing simplification of overall channel characteristics is in disequilibrium. The balance between erosion and deposition has been disrupted. This may be the result of major disturbance, changes to riparian vegetation, or to the supply of water, sediment or structural elements. Disequilibrium can also be caused by local disturbance or channel manipulation. If the changes or disturbance are temporary, the stream will often recover its former characteristics. If the changes are chronic, the stream will eventually reach a new, often simplified, equilibrium.

Effective restoration of aquatic habitat depends upon reestablishing watershed and stream processes to a range of variability that maintains a complex channel/floodplain system in dynamic equilibrium. This endeavor requires a body of knowledge encompassing geomorphology, hydrology and plant ecology, and also the societal will to adopt sustainable land use practices. At this time it is not clear to what degree ranges of natural variability can be tampered with before significant habitat simplification occurs; stream ecosystems have varying degrees of resilience. Alterations to watershed and stream processes exceeding the natural range of variability of those processes will inevitably alter the stream habitat and ecosystem. The degree of alteration we collectively find acceptable is the outstanding question.

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